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Accelerator Projects, Worldwide*

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At any given time one always has the feeling that the funding for basic research is tight and inadequate. But an overall examination of the current accelerator projects in the world at all stages of proposal, construction, and operation proves to be rather reassuring. The result of this survey is presented here in tabulated form, and the rationale and utility of these projects are discussed and compared.

Accelerator projects can be broadly classified in the following four categories:

1. High Energy Colliders - The pursuit of high energies or small dimensions for particle physics studies is the initial and basic motivation for the development of accelerators. The high energy frontier is now covered exclusively by colliders.

2. High Intensity, Medium Energy Accelerators - Machines of this category are useful for both particle and nuclear physics research.

3. Synchrotron Radiation Storage Rings - These machines have mushroomed during the past decade into a large and important category of accelerators. The synchrotron radiation from an electron beam travelling inside the dipole magnets or the undulators in a storage ring yields VUV and X-rays of unprecedented brilliance and brightness for studies of atoms, molecules, and condensed matters, and for industrial and medical applications. Most of these storage rings are in the energy range of 0.7 GeV to 7 GeV.

4. Low Energy Medical, Industrial and Research Accelerators - Large numbers of low energy accelerators of all types are used for atomic and nuclear research and for applications in industry and medicine.

In this paper we will describe principally projects of the first two categories.

High Energy Colliders

All recent projects aimed at high energies are colliders. We limit the discussion here to machines having actual or projected completion dates between 1985 and 1995. Geographically these are shown in the world map in Fig. 1. Hadron colliders are underlined, lepton colliders are not underlined, and the mixed collider HERA is underlined with a dotted line. This map contains all colliders that are either in construction or in operation, and two that are approved and are expected to be funded for construction in FY 1989. Altogether nine projects are included within the time period specified.

To compare the utility of hadron colliders with lepton colliders we need the concept of "reach" introduced by Llewellyn Smith. This concept is best illustrated by an examination of the energy dependence of high energy reaction cross-sections. This is given in Table 1 side-by-side for hadrons and leptons.

For lepton interactions at high energies the cross-sections vary roughly as s^{-1} where s is the square of the center-of-mass energy, and are independent of the mass-scale of the produced particle(s). The necessary luminosity of a lepton collider is, therefore, proportional to s. The coefficient of proportionality is clearly a soft parameter dependent sensitively on the design of the detector and the patience of the experimenter. The value given in Table 1 is only a ball-park number scaled from the parameters of LEP, $\mathscr{L} = 10^{31}\mathrm{cm}^{-2}\mathrm{sec}^{-1}$ at $\sqrt{s} = 0.1$ TeV.

The fact that the cross-sections are independent of the mass of the produced particle implies that the highest mass-scale M that can be reached (the "reach") is given simply by $\sqrt{s}$. This is the distinguishing characteristic of a lepton collider.

For hadron interactions the situation is quite different. First, the compositeness of hadrons results in energies of collisions between quarks and gluons much lower than the energy of the incident hadrons. Secondly, because of the strong interaction, low mass particles are produced in great multiplicities, thereby reducing the probability for production of high mass particles. Thus, in addition to the s^{-1} dependence, the cross-section is a sharply decreasing function of the ratio of the mass-scale reached, M, to the center-of-mass energy, $\sqrt{s}$. At high energies, available data indicate that $(M/\sqrt{s})^{-6}$ is a fair description of this function,. Thus, the "reach" depends on both the center-of-mass energy and the luminosity. The proportionality coefficient given in Table 1 is again a ball-park number obtained from the discovery of Z^0 and $W^{\pm}$ on $S\bar{P}PS$.

The "reach" gives a fair comparison between the capabilities of lepton and hadron colliders. However, for a given lepton collider one should check that the luminosity is adequate to make it a useful machine at all.

In Table 2 we list three colliders in operation; five colliders in construction the first of which, SLC, is now in the commissioning stage; and five proposed colliders of which the first two have been approved for funding in FY 1989. These projects are listed in the order of their actual or anticipated year of first operation.

Several interesting observations deserve mentioning:

1. The list is quite long and rather impressive. If all these projects stay on schedule we will be commissioning new facilities in the period of 1985-1995 at roughly a uniform rate of one per year.

2. Detectors are not included in the Cost entries. These entries are only rough approximations because of the rapidly changing currency exchange and inflation rates and in some cases, the inaccessibility of exact and reliable data. They nevertheless give a rough idea of the magnitude of the efforts involved. One notes that with the two approved proposals included the total cost of all the entries amounts to almost $7 billion, a very impressive sum.

3. One can get a "unit cost" by dividing the Cost by the "Reach." The is given in Table 3 which show clearly that the cost per "reach" is a monotomically decreasing

function of the "reach." This is presumably a demonstration of the principle of "economy of scale."

4. Except for S$\bar{\text{P}}$PS, all hadron colliders use superconducting magnets as indicated by Field entries of > 2T.

5. Despite the disadvantages, all high "reach" machines are hadron colliders. Even the rather futuristic and, so far, not quite ready-for-construction linear lepton colliders CLIC and VLEPP do not come close to the hadron collider SSC in "reach." Among hadron colliders the $\bar{p}p$ option is limited in "reach" by the achievable luminosity. It thus appears that at least for the present, the highest "reach" is obtained by pp colliders. However, this high "reach" is derived only from immense size and cost of the facility.

High Intensity, Medium Energy Accelerators

All so-called high energy phenomena also influence events at low energies, although in most cases the effects are greatly reduced in magnitude. This is even true for the search of some high mass particle whose existence can nevertheless be inferred from effects due to virtual processes on interactions at energies much below its production threshold. To detect these minute effects one needs to perform precision experiments. In addition to yielding information at high mass-scales, precision experiments can reveal new phenomena through studies of rare or forbidden events, violations of symmetry principles, etc. Because of the absence of strong interaction, precision lepton scattering experiments are further useful for probing the fine structures of nucleii and hadrons. In fact, since it appears that colliders with "reaches" much beyond, say, 10 TeV will be too costly to build, at least based on present day technology, it is likely that precision experiments will be the only approach to studying phenomena at extremely high energies. A good example and a case in hand is the proton decay experiment which performed at < 1 GeV (decay energy) is supposed to test for the symmetry of strong/electroweak interactions at the grand unification mass of 10^{15} GeV.

For precision experiments we need high luminosities and high luminosities are obtained by high intensity beams striking high density fixed material targets. A 100 μA beam with a cross-sectional area of 1 cm^2 striking a 1 mole target gives a luminosity of $\sim 4x10^{38} cm^{-2} sec^{-1}$. Both hadron and lepton high intensity accelerators have been proposed, but only one of these machines, CEBAF a continuous electron beam recirculating linac, has been approved and is now in construction. Most of these designs provide beams at several intermediate steps of energy to enhance their usefulness and rely upon the copious production of secondary and tertiary particles to provide beams of different particle species.

The concept of studying high energy phenomena by doing precision experiments at lower energies was discussed as early as the latter part of 1950's by physicists at MURA (Midwestern Universities Research Association). But the "high intensities" in those days were not very high (a few μA) and the "high energies" were obtainable at not excessively high cost and at not much lower luminosity. "High energies" today are getting to be rather difficult and expensive to come by.

In addition to CEBAF, four proposals for hadron facilities of this category are listed in Table 4. It is understandable that these proposals do not have the appeal of the high energy colliders, but the costs are substantially lower. Hopefully at least one of the high intensity hadron facilities proposed will someday be built.

Synchrotron Radiation Storage Rings

We list in Table 5 the electron (or positron) storage rings used for synchrotron radiation in the world by country. Only their energies, locations and status are given. Because of the very large number of these facilities there may be omissions in the table, but hopefully, they are not major ones.

Instead of high energy or high intensity as for the first two categories, the challenge in accelerator science and technology for these machines is the low beam emittance desired to maximize the brilliance of the synchrotron radiation emitted, and the maintenance of ultra-high vacuum in the presence of outgassing by the very intense synchrotron radiation. As VUV and X-ray sources, these machines yield brilliances many orders-of-magnitude higher than those obtainable from all other types of sources. The costs of these projects range from some $10M for the lowest energy to about $400M for the highest energy facilities.

We will not make further comments on this important category of accelerator projects except to point out the recent outcropping of the subcategory of industrial synchrotron radiation sources indicated by asterisks, *, in the table. These are storage rings in the energy range of 1/2 to 1 GeV and used for the manufacturing of VLSI chips by the method of X-ray lithography. It is expected that with X-ray lithography, feature resolutions of 1/4 μm or better can be achieved. At the present, using optical lithography the feature details are limited to ~ 1 μm. Rough estimates of the storage rings required if all VSLI chips are produced by synchrotron X-ray lithography give numbers in the hundreds. Similar conclusions on the magnitude of needs can also be drawn for medical applications of synchrotron radiation such as angiography. Thus, we can expect further and more extensive mushrooming of accelerator projects of this category in the near future.

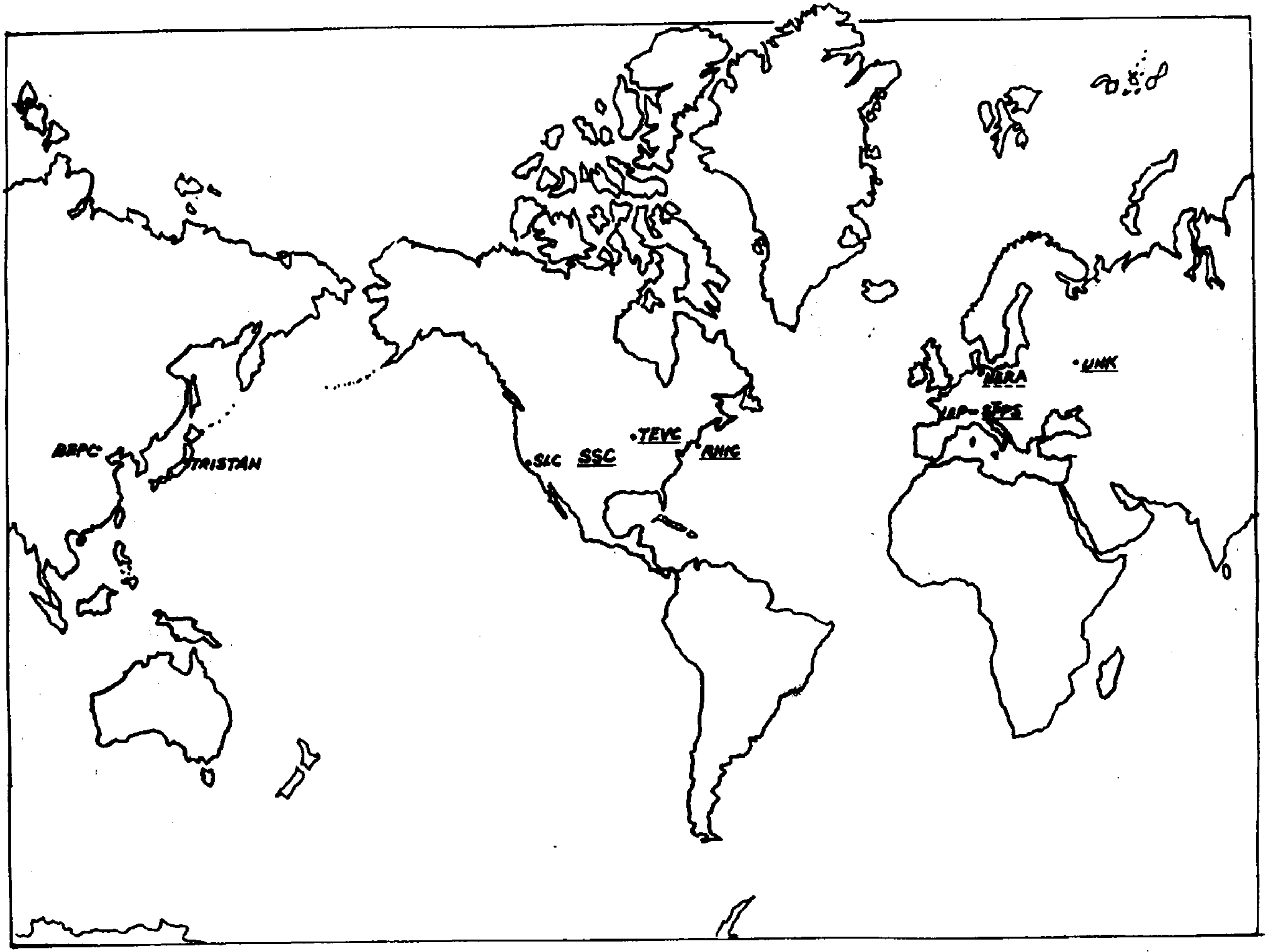

Figure 1. World map showing locations of high energy colliders.

Table 1. High Energy Reaction Cross-section, Luminosity, and "Reach"

	HADRON	LEPTON
Cross-section	$\sigma \propto \frac{1}{s} f\left(\frac{M}{\sqrt{s}}\right)$ $\simeq \frac{1}{s}\left(\frac{M}{\sqrt{s}}\right)^{-6} = \frac{s^2}{M^6}$ M = mass-scale reached	$\sigma \propto \frac{1}{s}$ s = square of C of M energy
Luminosity required	$\mathscr{L} \propto \frac{1}{\sigma} \propto \frac{M^6}{s^2}$	$\mathscr{L} \propto \frac{1}{\sigma} \propto s$ $= \left(\frac{\sqrt{s}}{0.1}\right)^2 \times 10^{31}$
"Reach"	$M \propto s^{1/3} \mathscr{L}^{1/6}$ $< \left(\frac{\sqrt{s}}{20}\right)^{2/3}\left(\frac{\mathscr{L}}{10^{33}}\right)^{1/6} \times 3.8$	$M < \sqrt{s}$

Note: M and $\sqrt{s}$ in TeV, $\mathscr{L}$ in $cm^{-2}sec^{-1}$

Table 2. High Energy Colliders with First Operation Between 1985 and 1995

Name [Laboratory]	Particles	Energy in GeV	Luminosity in $cm^{-2}sec^{-1}$	"Reach" in GeV	Year of 1st Operation	Circumf. in m [Field in T]	Cost in M$
In Operation							
$Sp\bar{p}S$ [CERN]	$\bar{p}$, p	270 + 270 315 + 315 450 + 450	4×10^{29} (4×10^{30})	100 (150) 130 (190)	1981 1985 (1987)	6912 [1.8]	150*
TEV. COLL. [FERMILAB]	$\bar{p}$, p	800 + 800 900 + 900 (1000 + 1000)	1×10^{29} (1×10^{30})	160 (260)	1985 1987 (1989)	6283 [4.4]	450
TRISTAN [KEK]	e^+, e^-	25 + 25 (30 + 30)	2×10^{30} (2×10^{31})	50 (60)	1986 (1989)	3018 [0.24 (0.29)]	500 [8×10^{10}¥]
In Construction							
SLC [SLAC]	e^+, e^-	50 + 50	6×10^{27}	100	1987	Linear	115.4*
BEPC [IHEP-PRC]	e^+, e^-	2.8 + 2.8	1.7×10^{31}	5.6	1988	238 [0.9]	80 [2.4×10^{8} Yuan]
LEP [CERN]	e^+, e^-	55 + 55 (100 + 100)	1.6×10^{31}	110 (200)	1989	26659 [0.06(0.11)]	750 [1.2×10^{9}SF]
HERA [DESY]	p, e^*	820 + 30	1.5×10^{31}	130	1990	6336 [4.5, 0.19]	425 [7.8×10^{8} DM]
UNK [IHEP-USSR]	p, p	3000 + 400 3000 + 3000	10^{32}	590 1200	1992	20772 [5.0, 1.0]	~ 1000

Table 2. High Energy Colliders with First Operation Between 1985 and 1995 (continued)

Name [Laboratory]	Particles	Energy in GeV	Luminosity in $cm^{-2}sec^{-1}$	"Reach" in GeV	Year of 1st Operation	Circumf. in m [Field in T]	Cost in M$
Proposed, Not Yet Funded							
RHIC [BNL]	Heavy ions	2 x 100 GeV/u [Au + Au]	4.4×10^{26}	-	1994	3834 [3.5]	350
SSC [-]	p, p	20,000 + 20,000	10^{33}	6000	1996	82944 [6.6]	3200
LHC [CERN]	p, p	8000 + 8000	1.4×10^{33}	3500	-	26650 [10.0]	-
	p, e^{*}	8000 + 50	2.7×10^{32}	520		[0.06,10.0]	
CLIC [CERN]	e^+, e^-	1000 + 1000	10^{33}	2000	-	2 x 12500 Linear	-
VLEPP [INP]	e^+, e^-	150 + 150 500 + 500	10^{32}	300 1000	-	2 x 1500 2 x 5000 Linear	-

Note: 1. Numbers in parenthesis are future upgrades.
2. * indicates partial cost only.

Table 3. Unit Cost of Colliders in Order of "Reach"

Collider	"Reach" in GeV	Cost in M$	Unit cost in M$/GeV"reach"
BEPC	5.6	80	14
TRISTAN	50 (60)	500	10
SLC	100	115*	1.15*
$S\bar{P}PS$	100 (150)	150*	1.5*
LEP	110 (200)	750	7
TEV. COLL.	160 (260)	450	2.8
HERA	130	425	2.4
UNK	590, 1200	~ 1000	~ 1.6
SSC	6000	3200	0.5
RHIC	-	350	-

Note: * indicates partial cost

Table 4. High Intensity, Medium Energy Accelerators

Name [Laboratory]	Particles	Energy in GeV	Current in μA	Cost in M$	Year of Completion	Accelerator type
CEBAF [CEBAF]	e^-	0.5 - 4.0	200 [Continuous]	216	1992	Recirculating supercon. linac
AHF [LANL]	p	2	500	500	-	Linac
		15	25			6Hz synchrotron
		60	25			6Hz synchrotron
TRIUMF II [TRIUMF]	p	3	100	350 [Cn$ 4×10^8]	-	50 Hz synch. + accum.
		30	100			10 Hz synch. + accum. and stretcher
EHF [-]	p	9	100	450	-	25 Hz synchrotron
		30	100			12.5 Hz synch. + accum. and stretcher
JHF [KEK]	p	2	200	-	-	50 Hz synchrotron
		3.2	100			0.5Hz stretcher/synch.
	Heavy ions	1.3 GeV/u	-			[same]
	p	30	-			-

Table 5. Synchrotron Radiation Storage Rings

Country	Name (Location)	Energy in GeV	Status+
Brazil	LNRS (Campinas)	2 - 3	C
China	BEPC (Beijing)	2.8	C
	HESYRL (Hefei)	0.8	C
	TLS (Hsinchu)	1.3	C
France	ESRF (Grenoble)	6	C
	ACO (Orsay)	0.54	O
	Super ACO (Orsay)	0.8	C
	DCI (Orsay)	1.8	O
Germany, Federal Republic	BESSY (Berlin)	0.75	O
	BESSY II (Berlin)	1.5 - 2.0	P
	* COSY (Berlin)	0.56	C
	Synchrotron (Bonn)	2.5	O
	ELSA (Bonn)	2.3	C
	DELTA (Dortmund)	-	P
	DORIS II (Hamburg)	3.7	O
	WILMA (Hamburg)	1 - 2	P
	* (Karlsruhe)		C
India	Indore I (Bhabha)	0.8	C
	Indore II (Bhabha)	-	P
Italy	ADONE (Frascati)	1.5	O
	New Ring (Trieste)	1 - 2	C
Japan	KSRS (Osaka)	5 - 6	P
	UVSOR (Okazaki)	0.6	O
	SOR Ring (Tokyo)	0.38	O
	TERAS (Tsukuba)	0.6	O
	NIJI-1 (Tsukuba)	0.3	O
	Photon Factory (Tsukuba)	2.5	O
	TRISTAN (Tsukuba)	30	O
	Accumulator Ring (Tsukuba)	6 - 8	O
	Super SOR (Tsukuba)	1.0	P
	* (Hitachi)	1.0	C
	, (NIT)		C
	* (Sumitomo Heavy Ind.)		C
	* (Sumitomo Electric)		C
Sweden	MAX (Lund)	0.55	O
	* (Scanditronix)	0.5	P
U.K.	SRS (Daresbury)	2.0	O
	* (Oxford Instrument)		C

Table 5. Synchrotron Radiation Storage Rings (continued)

Country	Name (Location)	Energy in GeV	Status+
U.S.A.	APS (Argonne)	7	P
	ALS (Berkeley)	1 - 2	C
	SURF II (Gaithersberg)	0.28	O
	CESR (Ithaca)	4.7 - 5.6	O
	SPEAR (Stanford)	3.5	O
	PEP (Stanford)	15	O
	Tantalus (Stoughton)	0.24	O
	Aladdin (Stoughton)	1.0	O
	VUV Ring (Brookhaven)	0.75	O
	X-ray Ring (Brookhaven)	2.5	O
	* (Brookhaven)		P
USSR	Siberia I (Moscow)	0.4	O
	Siberia II (Moscow)	2.0	C
	VEPP-2M (Novosibirsk)	0.67	O
	VEPP-3 (Novosibirsk)	2	O
	VEPP-4 (Novosibirsk)	5	O
	V3P (Novosibirsk)	-	P
	ARUS (Yerevan)	6	O

Note: + for the Status column: O = in operation, C = in construction, and P = in proposal.

* denotes industrial machines in the energy range of 0.5 - 1.0 GeV. They are generally without names.